

High priority R&D issues on Transport Barriers and their control in ITER

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ITER reference operation scenarios rely on the achievement of large plasma thermal energy ($W_{th} \geq 300$ MJ) based on the existence of transport barriers in the edge and, for steady-state operation, possibly also in the core plasma. Although there exist a large experimental database and some basic theoretical understanding of the characteristics of these barriers and their control, together with the requirements for their formation in present tokamaks, many important issues regarding these key topics and their integration with other ITER remain uncertain. Some of these issues are related to intrinsic properties of the ITER plasmas such as: low collisionality and high density, low external torque input, lack of central fuelling, etc.. Others are related to the specific ITER scenarios to achieve its goals (i.e., proximity to L-H threshold) and/or to edge plasma-wall interactions compatibility requirements (i.e., control of stationary and ELM transient power fluxes, He ash removal and control of core impurity contamination, etc.).

The paper will describe the physics basis and predictions regarding the properties of the regimes with transport barriers in ITER, their effect on plasma performance and the foreseen schemes for their control. In particular, the following aspects will be considered: the role of edge transport and neutral sources in determining the characteristics of edge transport barriers, the influence of toroidal field ripple on edge transport barrier characteristics, the role of plasma rotation and rotational shear in the triggering and sustainment of transport barriers, the integration of regimes with transport barriers and edge conditions leading to substantial power dissipation by edge radiation, the access and temporal evolution of transport barriers in conditions expected in ITER (i.e. varying heating power associated with alpha heating and closeness of edge power flux to H-mode threshold), the control of transport barriers and plasma transport by active means (such as by localised heating, controlled ELM triggering and suppression, etc.)

The experimental and modelling R&D required in the next years to consolidate the basis for the properties of transport barriers, their integration with other requirements of ITER operating scenarios, as well as that of the foreseen schemes for active barrier control (such as ELM control methods) in ITER will be described.

Impurity transport characterisation in JET operational scenarios

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*See Appendix of M.L. Watkins et al, Fusion Energy 2006 (Proc 21st Int Conf. Chengdu, 2006) IAEA.

Prediction and control of density and impurity profiles in long pulse and steady-state operation are needed for the design of a future fusion power plant. The behaviour of impurities is of particular importance in improved confinement discharges. In strong Internal Transport Barrier (ITB), a characterisation of impurity transport has already been done, and high Z impurity were shown to strongly accumulate [1,2] in accordance to the Z dependence of the neoclassical peaking. Recently, the development of advanced scenarios has evolved away from these strong ITB, towards achieving stable plasmas with high normalised pressure and current profiles ranging from the hybrid to the advanced tokamak [3]

At JET, the exploration of the q profiles domain for stability and confinement ranged from plasma with $q_{95} \sim 4$, $q_0 \sim 1$ at low δ (1.6-2.3MA/1.9-2.7T) [4] to plasmas with $q_{95} \sim 5$, $q_0 \sim 1$ to $q_0 \sim 2$ at high δ (1.1-1.6MA/1.6-2.3T) [5]. The transport of impurity was probed during this study via perturbative techniques with the introduction of a small quantity of impurities, either via short gas injection (for He (Z=2), Ne (Z=10) and Ar (Z=18)) or via laser ablation for metals such as Ni (Z=28) as well as recording the C (Z=6) density profiles. The transport coefficients, the diffusion D and the pinch velocity V, are determined with the help of an impurity transport code. In the highest achieved confinement discharges in this series, the steady-state scenario at $q_{95} \sim 5$ at 1.8T with $H_{98,y2} \sim 1.25$ and $\beta_N \sim 2.9$ [6], Ni was injected and a much weaker accumulation is observed than ITB plasmas. Similarly, strong Ni accumulation is not observed in higher confinement hybrid discharges at low δ with $q_{95} \sim 4$, $H_{98,y2} \sim 1.35$ and $\beta_N \sim 3$ at 2T. A comparison of the different scenarios will be made in terms of impurity peaking for both low and high Z, and possible difference in confinement region for impurity will be investigated. In addition, the transport of impurity, in particular W, was probed in higher current and field (2.65T, 1.8MA, $q_{95} \approx 4.7$) with weak ITB at mid-radius where a confinement of $H_{98,y2} \sim 1.2$ and $\beta_N \sim 2.7$ [6] was achieved.

These new results on discharges with $H_{98,y2} > 1$ will come in addition to the database of L-mode and H-mode already presented [7]. A picture of the behaviour of impurity at JET can be drawn and should shed light on mechanisms at play in the transport of impurity. In particular the role played by neoclassical transport, as well as observed conditions for the outward convection. The capability of present model (GS2) to predict the level of anomalous transport observed in the experiment will be tested.

[1] Takenaga Nucl. Fusion 43 (2003) 1235 [2] Dux Nucl. Fusion 44 (2004) 260 [3] Rimini IAEA 2008 [4] Hobirk EPS 09 [5] Challis EPS 2009. [6] Mailloux EPS 2009 [7] Giroud TTF 08

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First Results for ELM pacing via Vertical Position Jogs in NSTX

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Edge-Localized Modes (ELMs), if not mitigated or suppressed, will result in unacceptably large impulsive heat fluxes in future large tokamaks and STs. Possible mitigation strategies include small ELM regimes and ELM pacing via any of pellet injection, magnetic triggering, or vertical position jogs. A first set of experiments in NSTX in 2009 was successful in generating ELMs via vertical jogs. The downward jogs were generated within the isoflux control algorithm by requesting brief but large excursions in either, or both of, the magnetic axis vertical position (z_{maxis}) or the midplane separation between the inner and outer separatrices (dr_{sep}); the latter was found to be most efficient. In the best examples, discharges with ~ 15 Hz intrinsic ELMs had the frequency increased to ~ 30 Hz via ~ 4 cm peak-to-peak jogs in the plasma centroid location; the ELMs are generally triggered at the point when the plasma is lowest, or during the subsequent upward motion. However, not all jogs triggered ELMs, and for brief periods of time, the ELMs can occur more frequently than the jogs. The dependence of the triggering on the equilibrium dr_{sep} and recent vessel lithiumizations will be discussed, and the effects of the jogs on the profiles will be presented. Future plans for optimizing the ELM pacing will be described.

Pedestal parameters at high plasma current at JET

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**See Appendix of F R Romanelli et al Fusion Energy 2008 (Proc 22nd Int Conf Geneva, 2008) IAEA, (2008)*

New diagnostic capability for pedestal measurements and new IR measurements with high temporal and spatial resolution, as well higher neutral beam heating have motivated JET to revisit the high current programme last carried out in 1997 [1].

This paper presents the recent results aiming at studying in detail the pedestal parameters and its dependence with plasma current and β_N . The study of pedestal parameters for discharges with pedestal close to ITER ($T_{ped} \sim 3-4\text{keV}$, $n_{eped} \sim 1e20$, $v^* \sim 0.01$ and $\rho^* \sim 2.06e-3$) in absolute value is also addressed.

These experiments were performed at low triangularity, to stay within the vessel force limits, with $\delta_{avg} \sim 0.25$. The data set includes a β_N scan at constant v^* for plasma currents from 2.2MA up to 3.8MA at a fixed q_{95} of 3 with confinement enhancement factor of ~ 1 . Pulses with plasma currents up to 4.3MA with q_{95} of 2.65 and $\beta_N \sim 1.5$ are also included, providing unique data on H-mode baseline scenario and pedestal at high current and $q_{95} < 3$.

Previous experiments have generated H-modes at $I_p \geq 3.8\text{MA}$ but these show poor confinement quality except in DT. The results, to date, show that at high current is not possible to maintain a steady state ELMy H-mode despite the input power ~ 2 above power threshold and $\beta_N \sim 1.5$. These pulses have low ELM frequency and mixed type I/III phases and an average confinement of ~ 0.9 . The lost of confinement is explained by the loss of edge pressure during the type III phases that follow a type I ELM. At the highest current (4.3MA) this effect was more pronounced and eventually a back transition to L-mode occurred. Marginal power above the threshold power, vessel conditioning, large pedestal temperature crash causing a change of edge stability, large losses post ELM before pedestal re-grows are possible causes for this transient ELM behaviour and consequently poor confinement that will be discussed in the paper.

[1] L D Horton, NF1999

H-Mode Pedestal Structure and Transport in Hybrid Plasmas During Magnetic Perturbation in the DIII-D Tokamak*

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The effect of resonant magnetic perturbation (RMP) on the H-mode pedestal structure is studied in hybrid discharges in the DIII-D tokamak. The empirical window for complete edge localized mode (ELM) suppression appears to be the same as in standard H-mode plasmas, which is $3.5 < q_{95} < 3.9$. A reduction in the pedestal bootstrap current during RMP is inferred through a decrease in q_{95} at fixed I_p/aB_T , consistent with the measured reduction in the edge pressure gradient. The parallel current profile in the pedestal is consistent with the Sauter model, both before and during RMP. Although ELM suppressed hybrid discharges are calculated by the ELITE code to be stable to peeling-ballooning modes during RMP, small amplitude ELMs are observed to return when the rotation frequency becomes small or when q_{95} is outside the resonance window for ELM suppression. The presence of small amplitude ELMs during RMP is associated with an increase in pedestal electron temperature and a decrease in the calculated magnetic field line diffusion. These are probably not Type I ELMs because peeling-ballooning stability is maintained. The pedestal height and width in these cases will be compared with predictions from the EPED1 model.

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Confinement and ETB studies of JET hybrid discharges

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In contrast to the H-mode scenario, the JET hybrid scenario uses a modified current and heating waveform to give a broader q-profile ($q \geq 1$) and access to higher β_N . 2006-7 JET studies indicated that confinement in the hybrid scenario at high β_N , crucial for its use as an ITER scenario, was similar to that of H-modes, strongly dependent on ETB physics and affected by plasma shape. To study this in more detail, experiments have been performed in which β_N was scanned at fixed n_e , B and I, by varying input power, in both the hybrid scenario and matched H-modes. To assess the shape effect, two sets of scans were performed at both low, $\delta \approx 0.2$, and high, $\delta \approx 0.4$, triangularity. Improved diagnosis was exploited to study the ETB physics in detail. In both scenarios, the presence of NTMs was associated with reduced normalised global confinement, $\leq 25\%$ for 3/2s and $\leq 15\%$ for 4/3s, but the hybrid scenario reached higher β_N (≤ 3.0) before encountering these modes. In the absence of these modes, both scenarios have similar confinement properties, with $H_{98(y,2)} = 1.1-1.3$, significantly higher than in previous studies. The absence of NTMs together with the development of high clearance shapes, associated with lower SOL densities, is shown to account for much of this change. The direct impact of q-profile on confinement is also considered. Across the whole experimental dataset, the energy confined by the plasma and the ETB alone is strongly linearly correlated. For $\delta \approx 0.2$, $H_{98(y,2)}$ and β at the ETB top, β_{ETB} , increases with increasing power. In contrast, for $\delta \approx 0.4$, $H_{98(y,2)}$ is weakly affected by power and β_{ETB} saturates at high power. This behaviour is compared with ETB models based on the stability of ballooning-peeling modes. All of these results are compared with the wider JET hybrid and H-mode database and implications for ITER discussed.

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Calculations of Non-ambipolar Transport in Tokamaks and ITER

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Small non-axisymmetric perturbations of the magnetic field can greatly change the performance of tokamaks through non-ambipolar transport. The recently generalized analytic calculations of the non-ambipolar transport have shown that the consistency between theory and experiment can be significantly improved by two effects [J.-K. Park, et al., Phys. Rev. Lett. **102**, 065002 (2009)] : (1) The small fraction of trapped particles for which the bounce and precession rates of particles resonant. (2) The non-axisymmetric variation in the field strength along the perturbed magnetic field lines rather than along the unperturbed magnetic field lines. Most apparent effects can be found in toroidal momentum transport and by a toroidal rotational damping associated with Neoclassical Toroidal Viscosity (NTV). Particle and heat transport by non-axisymmetric perturbations are also implied by Onsager symmetry, and can be important hidden features of pedestal structure modifications by Resonant Magnetic Perturbations (RMPs) associated with Edge Localized Modes (ELMs). Various experiments for NTV rotation braking in NSTX and DIII-D will be compared with theoretical predictions, and the expected sensitivity of ITER to non-axisymmetries will be presented. Also, implications of particle and heat transport driven by RMPs on pedestal structure and ELMs will be discussed.

L-H and H=1 access experiments in JET and implications for ITER

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The timely achievement of $Q=10$ in the ITER inductive scenario requires that H-mode with confinement enhancement factor, $H_{98y1}=1$, at high density, $n_e=0.8n_G$, be produced with the additional heating power of 73 MW initially installed in ITER. The preparation of the H-mode scenario, such as ELM and MHD control and validation of H-mode scaling, will be carried out during the non-active phase of the ITER programme (Hydrogen and Helium operation) and during the Deuterium phase of ITER operation. It is therefore essential for ITER to also be able to achieve the H-mode regime with 73 MW also in these phases of preparation for DT operation.

This paper will present recent results of JET experiments on the L-H threshold and H=1 access, will highlight relevant past JET results and will discuss their implications for ITER. Previous JET experiments in H, D, T and DT have shown that the L-H threshold power has an inverse dependence on mass [1]. The same experiments and new results, have also demonstrated that the L-H threshold is the same for NB and IC heated H-modes, highlighting that there is no issue for H-mode access, at least for ICH versus NBI, with the ITER heating mix. ITER will operate with a toroidal field ripple higher than the one in JET (ripple of 0.08% at the separatrix in JET vs $\approx 0.5\%$ in ITER). Experiments where the ripple was varied from 0.08 to 1% found that the L-H threshold did not depend on ripple [2]. The substantial variation of plasma toroidal rotation achieved with variations of ripple and the additional heating mix indicates little effect of toroidal rotation on P_{LH} . In addition, recent experiments have shown that the application of EFFF field for ELM amelioration does not affect the L-H threshold.

Dedicated experiments in JET found that H-modes energy confinement, as predicted by the scaling for Type I ELMy H-modes, i.e. $H_{98(y,2)} = 1$, required heating power larger than P_{LH} [3]. This is because at powers just above P_{LH} the H-mode has Type-III ELMs. Type-III ELMy H-modes have lower confinement than type-I ELMy H-modes by approximately 15-20%. The same experiments showed that the power required to achieve and maintain Type-I ELMs can be empirically expressed as $P_{TypeI} = \alpha P_{LH}$ (i.e. P_{TypeI} has similar dependency on n_e , B_t and ion mass as the L-H threshold scaling predictions). The proportionality factor, α , varies in JET from ≈ 1.1 to ≈ 2 . This is not a random variation since conditions for the variation of α can be identified, and reproducibility can be achieved. For example, larger α is typically associated with low density/collisionality and low triangularity. This variation could have two underlying reasons. First, L-H threshold and Type-III ELM stabilization are different phenomena and hence can depend on different parameters. In addition, P_{LH} might depend on hidden variables not included in the scaling [2].

As the power is increased from the L-H power threshold, there are three power ranges with different ELM behaviour: Type III ELMs, mixed periods of Type I and Type III ELMs, and finally, when $P > P_{TypeI}$, Type I ELMs for the entire duration of the discharge. When the ripple is increased the measured P_{LH} and the power range where Type III ELMs are observed do not change, but the range of power where mixed ELM behaviour is observed becomes larger, i.e. P_{TypeI} increases. This indicates that P_{TypeI} and P_{LH} have different dependencies on ripple.

A lower ($\sim 30\%$) P_{TypeI} was found in JET at higher plasma triangularity, for a variation of δ from 0.2 to 0.33. For the same I_p/B_T , plasmas with higher triangularity have in JET higher natural density and lower temperature. When the same comparison is done at the same density, where high triangularity plasmas have higher temperature, the difference in P_{TypeI} becomes smaller, indicating a possible dependence of α on collisionality. The experiments at ITER like triangularity ($\delta > 0.4$) highlighted two other effects. First, at low power above P_{LH} these plasmas can display continuous core density peaking with low frequency Type I ELMs. Second, experiments with kicks to increase the naturally low ELM frequency were successful in lowering P_{TypeI} . Those observations demonstrate that ELM dynamic and possibly core effect should be included in the evaluation of P_{TypeI} .

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Progress in the Development and Validation of the EPED1 Model of the Pedestal Height and Width*

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Accurate prediction of the pressure at the top of the edge barrier (or “pedestal height”), and its variation with key parameters, is crucial to prediction and optimization of confinement and overall fusion performance of ITER and tokamak fusion reactor designs. We have recently developed a model, EPED1, which predicts the pedestal height and width using a simple set of inputs that can be known before an experiment is conducted. The EPED1 model employs two constraints: 1) Stability to intermediate wavelength peeling-ballooning modes, as calculated using the ELITE MHD code and sets of model equilibria, and 2) Near criticality to short wavelength kinetic ballooning modes (KBM), as approximated by a simple formula. These two constraints determine the two unknowns, pedestal height and width, and allow direct comparison to experiment and predictions for future devices.

The EPED1 model has been initially tested against an extensive set of observations on the DIII-D, JET, and JT-60U tokamaks, finding good agreement, with a ratio of predicted to observed pedestal height of 1.02 ± 0.13 in an initial set of 41 cases. Here we discuss continuing validation of EPED1 against a wide range of observations on multiple devices, including direct tests of the KBM constraint, and pedestal predictions for ITER in various regimes of operation. We also propose a simple expression that can be used to approximate EPED1 predictions across a limited range of input parameters. Ongoing improvements to the model, including development of a more precise KBM model based entirely on direct electromagnetic gyrokinetic calculations, and improvements in the model of diamagnetic stabilization of peeling-ballooning modes, are discussed.

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Collisionality scan of confinement in MAST H-mode plasmas

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Design of future tokamaks such as ITER/DEMO and Component Test Facility based on spherical tokamak (ST-CTF) [1], requires adequate physics basis for predicting energy confinement, heat transport and fuelling requirements. In spherical tokamaks, the values of energy confinement broadly agree with those in conventional tokamaks, i.e. IPB98y2 scaling, but some parametric dependencies are different [2, 3]. In particular the dependence of energy confinement time on toroidal magnetic field is close to linear, in contrast to IPB98y2. It has been suggested [2] that this could be a consequence of weaker safety factor q and stronger collisionality dependence of energy confinement and heat transport compared to conventional scalings. The dependence on normalised collisionality ν^* is particularly important for spherical tokamaks because this is the main extrapolation variable from MAST and NSTX to devices such as ST-CTF, while there is no extrapolation in normalised Larmor radius ρ^* and extrapolation in β is very small. The aspects of ν^* -scaling might, however, affect the models and scalings used also for ITER/DEMO.

The collisionality dependence of energy confinement in MAST H-mode plasma has been tested directly using a factor of four scan in ν^* while the change in other dimensionless parameters q , ρ^* and β is small. The collisionality exponent in the energy confinement scaling, $\tau_E B \propto \nu_*^{-x_\nu}$, is found to be at the higher end of the interval $x_\nu = 0.2 - 0.75$ reported in conventional tokamaks [4]. The study of global dependence is assisted by local heat transport analysis facilitated by upgraded Thomson scattering, charge exchange and MSE diagnostics. A similar test of the ν^* dependence of particle confinement using deuterium pellets is planned. Possible candidates for dominant transport mechanisms will be discussed.

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Fine-scale zonal flow generation from trapped electron mode turbulence

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Most existing zonal flow generation theory^{1, 2} has been developed with a usual assumption of $q_r \rho_{i0} \ll 1$ (q_r is the radial wave number of zonal flow, and ρ_{i0} is the ion poloidal gyroradius). However, recent nonlinear gyrokinetic simulations of trapped electron mode (TEM) turbulence exhibit a relatively short radial scale of the zonal flows with $q_r \rho_{i0} \sim 1$.^{3, 4, 5} So far, there are very few theoretical works on ZFs in CTEM turbulence driven by the trapped electron precession drift resonance. This work reports an extension of zonal flow growth calculation to this short wavelength regime via the wave kinetics approach. A generalized expression for the polarization shielding for arbitrary radial wavelength⁶ which extends the Rosenbluth-Hinton formula in the long wavelength limit⁷ is applied. The variation of the ZF growth rate normalized to the CTEM intensity in gyro-Bohm units with plasma parameters is also investigated.

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Non-diffusive transport in collisionless trapped electron mode turbulence

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A prominent candidate for the electron heat transport in high temperature toroidal plasmas is collisionless trapped electron mode (CTEM) turbulence with a characteristic eddy size of the ion gyroradius. Large scale simulations of CTEM turbulence using gyrokinetic toroidal code (GTC) finds the electron heat transport exhibiting a gradual transition from Bohm to gyroBohm scaling when the device size is increased, which could be induced by large turbulence eddies, turbulence spreading, and non-diffusive transport process. Radial correlation function shows that CTEM turbulence eddies are predominantly microscopic but with a significant tail in the mesoscale. The mesoscale streamers result from a dynamical process of radial streamers breaking by zonal flows and merging of microscopic eddies. It is further found that the radial profile of the electron heat conductivity only follows the profile of fluctuation intensity on a global scale, whereas the ion transport tracks more sensitively local fluctuation intensity. This suggests the existence of a nondiffusive component in the electron heat flux, which arises from the ballistic radial ExB drift of trapped electrons due to a combination of the presence of mesoscale eddies and the weak detuning of the toroidal precessional resonance that drives the CTEM instability. In contrast, the ion radial excursion is not affected by mesoscale eddies due to the parallel decorrelation, which is not operational for trapped electrons because of the bounce averaging process associated with the fast parallel motion of electrons. This is confirmed by our comprehensive analysis of kinetic and fluid time scales showing that zonal flow shearing is the dominant decorrelation mechanism. Supported by SciDAC GPS-TTBP Center.

Scaling of Energetic Particle Transport by Microturbulence

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The diffusion of energetic particles by microscopic ion temperature gradient turbulence is studied in large-scale simulations using a global gyrokinetic toroidal code (GTC). The ion radial excursion is found to be a diffusive process and thus the diffusivity as a function of the energy and pitch angle can be calculated using the random walk model. We find that the diffusivity decreases drastically for high-energy particles due to the averaging effects of the large gyroradius and orbit width, and the fast wave-particle decorrelation. At high energy, the diffusivity dependence on the particle energy (**Fig. 1**) is found to be E^{-1} for purely passing particles (magnetic moment $\mu=0$) and E^{-2} for

deeply trapped particles (parallel velocity $v_{\parallel}\sim 0$).

A quasilinear theory is invoked to explain the different asymptotic scaling of passing and trapped particles. For the deeply trapped particles (**Fig. 1b**), the gyro- and orbit averaging each gives rise to a dependence of D on $E^{-1/2}$

when taking a large argument expansion of the Bessel function. The decorrelation of the drift-bounce resonance gives rise to another dependence of D on E^{-1} . For the purely passing particles (**Fig. 1c**), orbit averaging and parallel decorrelation each gives rise to a dependence of D on $E^{-1/2}$.

Therefore, for the isotropic velocity distribution such as α -particles, the diffusivity is contributed mostly by passing particles with an energy scaling of E^{-1} (**Fig. 1a**). Work supported by US DOE SciDAC GSEP Center.

FIG. 1. Dependence of energetic particle diffusivity on particle energy E/T_e : (a) for isotropic velocity, (b) for passing particles ($\mu = 0$), and (c) for deeply trapped particles. The points are simulation results. The solid lines are theoretical scaling laws.

